PRELIMINARY MODEL TESTS OF A FLUME FOR MEASURING DISCHARGE OF STEEP EPHEMERAL STREAMS

A. R. Chamberlain

PRELIMINARY MODEL TESTS OF A FLUME FOR MEASURING DISCHARGE OF STEEP EPHEMERAL STREAMS

by
A. R. Chamberlain

prepared for the

Rocky Mountain Forest and Range Experiment Station

Civil Engineering Department
Colorado A and M College
Fort Collins, Colorado

February 1957

PRELIMINARY MODEL TESTS OF A FLUME FOR MEASURING DISCHARGE OF STEEP EPHEMERAL STREAMS

by
A. R. Chamberlain

prepared for the
Rocky Mountain Forest and Range Experiment Station

Civil Engineering Department
Colorado A and M College
Fort Collins, Colorado

February 1957

CONTENTS

PRELIMINARY MODEL TESTS OF A FLUME FOR MEASURING DISCHARGE OF STEEP EPHEMERAL STREAMS

by
A. R. Chamberlain

SYNOPSIS

A number of open channel flow measuring devices were reviewed in an attempt to find one that would function satisfactorily in sediment-laden ephemeral streams on steep slopes. A trapezoidal Venturi (modified WSC or Chamberlain) flume was decided upon. Two designs of this flume, at a 1:7 scale ratio, were tested in the Colorado A and M College Hydraulics Laboratory. The bottom of the flume was set at 5 per cent. A calibration curve was obtained for each design, with each of three approach channel roughnesses.

The tests indicated that a well defined calibration curve could be established for the flume shown in Fig. 1. Upstream roughness, however, affected the calibration curve over the supercritical flow range.

The work reported herein was somewhat exploratory in nature. It was found that sometimes the device must operate with supercritical velocity throughout the structure, while at other times the flow changes from supercritical to subcritical, or oscillates back and forth between stages. With extremely low flows the device operates like a conventional critical depth meter.

The problem of measuring flows with open channel structures on steep slopes of sediment-laden ephemeral streams is extremely difficult, as one can easily adjudge. The transverse and oblique standing waves that exist in open channel structures under such conditions are analogous to the sonic barrier encountered by supersonic aircraft.

PRELIMINARY MODEL TESTS OF A FLUME FOR
MEASURING DISCHARGE OF STEEP EPHEMERAL STREAMS

by
A. R. Chamberlain

INTRODUCTION

In late 1956 the immediate need arose for a flow measuring device that could be constructed at selected locations along some small open channel ephemeral streams. The slope of the streams ranged from 3 to 8 per cent; discharges were estimated to be as high as 300 cfs, with measurements required down to about 0.5 cfs. Heavy sediment loads were expected, including large boulders, trees and other detritus. A continuous record of discharge was desired.

It would be difficult to conceive of a much more difficult problem to resolve. The flow in the natural streams under consideration will sometimes be in the subcritical regime, sometimes supercritical, and then of course the extremely unstable transitions from subcritical to supercritical and back to subcritical take place. The discharges to be measured cover a very large range. Boulders and trees will plug any device that materially contracts the stream. Significant ponding of the flow cannot be tolerated because sediment will deposit in front of the structures, completely changing entrance conditions each time a flood passes.

This report will cover the following by sections: I - Brief Review of Some Devices Considered; II - The Trapezoidal Venturi Flume; III - Some Notes on Theory; IV - The Preliminary Model Tests; V - Results of Preliminary Model Tests; VI - Recommendations; VII - Summary of Laboratory Data; and VIII - Bibliography.

I. BRIEF REVIEW OF SOME DEVICES CONSIDERED

The possible methods that one could utilize to solve the problem posed in the Introduction can be conveniently grouped into:

1. Chemical methods,
2. Orifices,
3. Sonic,
4. Electromagnetic,
5. Wiers,
6. Current meters, and
7. Flumes.

Other devices do exist, of course, but will not be considered here. A partial bibliography of literature is appended at the end of the report.

Chemical methods, while offering some promise, do not appear to be practical at this time on ephemeral streams at sites that cannot be reached quickly, and sediment concentration and chemical composition may affect results. Unsteady flows add to the difficulties. Usually several men are required to carry out the measurements. Radioactive isotope technique offers some interesting possibilities for the future.

Orifices are impractical because boulders and rocks will plug them. Sediment will change approach conditions because the structure containing the orifice will cause ponding -- hence allow sediment to deposit.

Sonic and electromagnetic equipment may someday be the answer to measuring the discharge of such streams as those considered here. At the present time a tremendous amount of research is still necessary. Sediment load will, in some cases, affect the calibration of such equipment -- and no information is available on the sediment load of the streams under consideration.

Current meters and Pitot tubes cannot be employed unless someone is present at the rating station when a flood passes. Further, the stage may change so rapidly that velocity profiles cannot be obtained. Sediment will cause no end of difficulty.

Weirs (sharp-edged broad-crested, parabolic, triangular, Columbia, Cipoletti, rectangular, etc.) are in general unsatisfactory because aggradation of sediment changes approach conditions. Aggradation will occur every time a sediment laden stream in supercritical regime passes through a hydraulic jump in the pond upstream from the contraction, soon filling the pond with sediment so that the stream approaches the weir at supercritical velocity. There are no data available on flow over weirs with supercritical approach velocities; all those data available assume subcritical flow conditions upstream of the structure. Furthermore, once the pond has filled with sediment, the weir becomes nothing but a drop structure.

Flumes offer a possible means of measuring flows at all velocities. They can be designed to pass sediment. However, apparently none of the flumes commonly utilized have been calibrated with supercritical approach velocities. Scour problems will be severe unless the structures are on rock. Waves can be extremely high and dangerous when the flow is supercritical.

The Parshall flume and similar flumes having vertical wall contractions are not satisfactory for ephemeral streams because the range of discharge they can handle is very limited. In addition, trees and boulders will easily clog them. The flumes developed by Crump, Balloffet, Inglis and de Marchi are examples of flumes with vertical walls but different transition forms. The H, HS and HL flumes are further examples.

A limited number of studies have been carried out on flumes of trapezoidal cross-section. Among the studies reported are the tests on the San Dimas flume, the work of the U. S. Bureau of Reclamation at Boise, Idaho, tests by V. M. Cone and, more recently, research by A. R. Chamberlain. These devices are the most promising because they can be designed to cover a large range of discharges, and pass boulders and trees. However, the standing wave problem can be severe.

II. THE TRAPEZOIDAL VENTURI FLUME

After careful consideration a flume of trapezoidal cross-section as shown in Fig. 1 was picked for laboratory testing. The floor of the flume and approach channel was set at a 5 per cent slope.

Such a flume can handle a very large range of discharges, but perhaps not quite 0.5 to 300 cfs. The lower limit is difficult to attain. A slope of 5 per cent should pass most sand and pebble sediments; this slope is a compromise between 3 and 8 per cent. Large boulders will roll through the structure. A recorder can be installed that will operate anytime a flood passes, whether an attendant is present or not. Therefore, since the trapezoidal Venturi flume may fulfill the conditions set forth, the decision was made to try it, first in the laboratory and then in the field.

In earlier works Chamberlain (9), Cone (12) and Parshall (34) all tested trapezoidal Venturi flumes with a plane horizontal floor. All these earlier researches were directed toward developing a critical depth flume, i.e., with subcritical velocities in the approach channel, critical depth within the structure and a hydraulic jump or supercritical flows in the lower reaches of the flume. No data are available on such flumes when the approach velocity is supercritical. Furthermore, the data available for trapezoidal Venturi flumes, including the San Dimas flume, are for structures with side slopes too steep to be useful for the problem studied herein.

Referring to Fig. 1 and comparing it to the structural designs employed by Chamberlain, Cone and Parshall, one finds that the downstream transitions of the earlier designs have been omitted. This was done because scour downstream from the proposed structures for which the tests reported herein

were conducted was assumed to be of negligible importance -- the structure will be on granite or some similar durable rock. Further, the experimental structures to be built as a result of these tests should be located in regions where spray and waves can be tolerated. Scour and uplift can be a serious problem when the velocities are supercritical throughout the structure.

III. SOME NOTES ON THEORY

A complete theory for supercritical, critical and subcritical flow through a trapezoidal Venturi flume is not available. Furthermore, such a theory would be extremely difficult to work out -- the flow at some stages is synonomous to the sonic barrier that is still causing the aerodynamicists so much trouble.

A theory is readily available for very low discharges, because the flume will then operate like the conventional critical depth flow meter. Cone (12) has derived theoretical discharge equations for specific cases on the basis of the Bernoulli equation and continuity. His equations, however, neglect the affects of friction. Chamberlain (9) used the momentum theory for developing a more general treatment of flow through trapezoidal sections. His results, however, are about identical to those obtained from the energy concept for the tests reported.

For the high discharges, which approach the flume at supercritical velocity, the work by Ippen, et al (24) is classic. Formulas are presented for supercritical velocity flows in transitions, but all the transitions are constructed of vertical walls. Hence, the results are not readily applicable, except in principle, to the problem involved here.

However, assuming a specific flume design has been decided upon, an adequate criterion for similarity of model and prototype for the purpose of obtaining a calibration curve will be the Froude number

$$Fr = \frac{V}{\sqrt{\frac{\Delta \gamma}{\rho} \frac{A}{T}}}, \qquad (1)$$

where V is a mean velocity, $\Delta\gamma$ is a difference in unit weight of two fluids, ρ is a mass density, A is an area normal to the direction of flow and T is the top width of the water surface at the cross-section of area A .

In this study $\Delta\gamma$ is the difference in unit weight of air and water and ρ is the mass density of water. For practical purposes $\Delta\gamma/\rho = g$, the gravitational constant. Letting V be the mean velocity at the section of area A ,

$$Fr = \frac{Q}{\sqrt{g}\ \sqrt{\frac{A^3}{T}}} \quad . \tag{2}$$

From the algebra, letting the subscript p designate prototype, m designate model, and λ the scale ratio, one finds

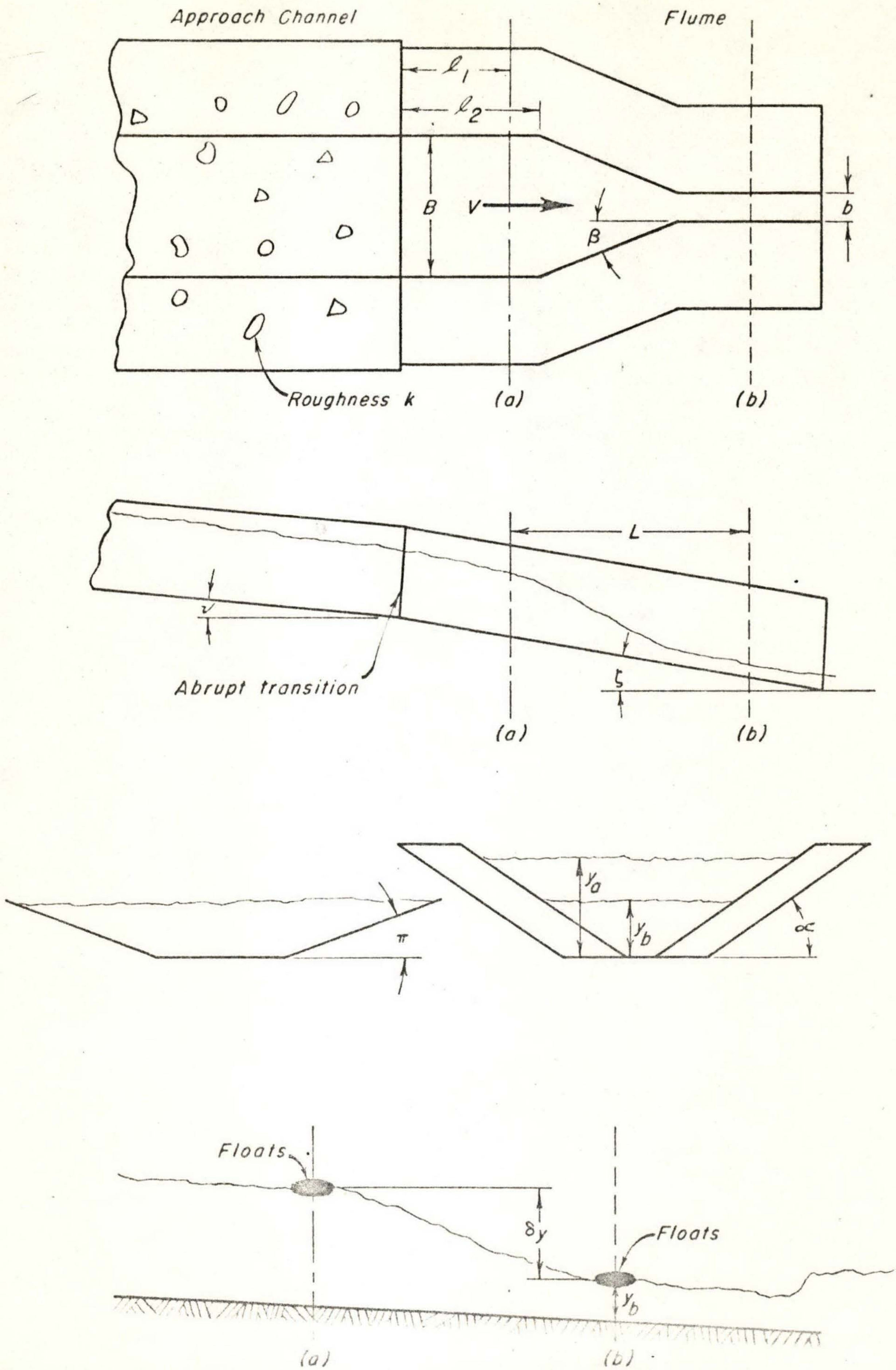
$$\begin{aligned} Q_p &= \lambda^{5/2}\ Q_m \ , \\ L_p &= \lambda\ L_m \ , \end{aligned} \tag{3}$$

where L is any length. Eqs 3 form the basis of all tests reported herein, with $\lambda = 7$ ($\lambda^{5/2} = 135$).

The foregoing discussion does not yield any information on the mechanics of the flow through flumes. Passing to a dimensional analysis of the problem one has (referring to "Nomenclature for Dimensional Analysis" on the following page and denoting by μ the dynamic viscosity of the mixture of water and sediment),

$$\phi_1(V\ ,\mu,\rho,\Delta\gamma,\ l_2\ ,\ B\ ,\ b\ ,\ k\ ,\frac{A}{T},\alpha,\beta,\kappa,\nu,\xi) = 0 \ , \tag{4}$$

or,



Nomenclature for Dimensional Analysis

$$\frac{V}{\sqrt{\frac{\Delta\gamma}{\rho}\frac{A}{T}}} = \phi_2 \left(\frac{V\frac{A}{T}}{\frac{\mu}{\rho}}, \frac{l_2}{\frac{A}{T}}, \frac{b}{\frac{A}{T}}, \frac{k}{\frac{A}{T}}, \frac{B}{\frac{A}{T}}, \alpha, \beta, \pi, \nu, \xi\right) . \tag{5}$$

This may be transformed to

$$\frac{V}{\sqrt{\frac{\Delta\gamma}{\rho}}\sqrt{\frac{A}{T}}} = \phi_3 \left(\frac{V\frac{A}{T}}{\frac{\mu}{\rho}}, \frac{l_2}{B}, \frac{b}{B}, \frac{k}{\frac{A}{T}}, \frac{B}{\frac{A}{T}}, \alpha, \beta, \pi, \nu, \xi\right) . \tag{6}$$

For most cases studied herein the Reynolds number may be dropped and $\Delta\gamma/\rho \cong g$

Assuming this,

$$\frac{Q}{\sqrt{g}\sqrt{\frac{A}{T}}} = A\phi_4 \left(\frac{k}{\frac{A}{T}}, \frac{l_2}{B}, \frac{b}{B}, \frac{B}{\frac{A}{T}}, \alpha, \beta, \pi, \nu, \xi\right) . \tag{7}$$

Hence, the discharge equation is

$$Q = \frac{\phi_4}{\sqrt{2}} A \sqrt{2g\, A/T} , \tag{8}$$

where

$$\phi_4 = \phi_4 \left(\frac{k}{\frac{A}{T}}, \frac{l_2}{B}, \frac{b}{B}, \frac{B}{\frac{A}{T}}, \alpha, \beta, \pi, \nu, \xi\right) .$$

The term $\frac{A}{T}$ is the average depth of flow at a section normal to the flow of area A .

For subcritical flow conditions, with an observer at section b,

$$\begin{aligned} A_b &= y_b\,(b + y_b \operatorname{ctn}\alpha) , \\ T_b &= y_b\,(b + 2y_b \operatorname{ctn}\alpha) , \end{aligned} \tag{9}$$

from which

$$Q = \sqrt{\frac{b + y_b \operatorname{ctn}\alpha}{b + 2y_b \operatorname{ctn}\alpha}} \left(\frac{\phi_4}{\sqrt{2}}\right) A_b \sqrt{2gy_b} . \tag{10}$$

For supercritical flow, with the observer again at b and replacing $\frac{A}{T}$ by y_b as read on a piezometer at some fixed point on the side slope of the throat section,

$$Q = \left(\frac{\phi_4}{\sqrt{2}}\right) A \sqrt{2gy_b} \quad . \tag{11}$$

In this case it is not possible to derive a simple expression for A .

Comparing Eqs 10 and 11, realizing that A is somewhat indeterminate in Eq 11, it becomes evident why it is more difficult to deal with supercritical flows. Even y_b in Eq 11 is somewhat ambiguous, in that it does not correspond to any actual flow depth. However, probably the most important point to study is the functional dependency of ϕ_4 .

The term $k/(A/T)$ is the relative roughness. In many cases, particularly subcritical flows, this term may be neglected. The parameter l_2/B is important only for supercritical flows. Assuming an observer is recording a piezometer head at some point in the throat, the head he sees will depend on the value of l_2/B because of the oblique standing waves. The b/B term serves as measure of the degree of contraction in the flume and $B/(A/T)$ is a measure of the width to depth of flow in the flume.

In view of the already evident difficulties associated with a theoretical analysis of the supercritical flow regime, the laboratory phases of the work concentrated on that regime. Hence, since only limited laboratory work was possible on the subcritical flow regime, a theoretical discharge equation is presented at this time. Perhaps later work will permit running laboratory experiments to verify the theory.

Let $\nu \cong \zeta$ and $l_1/l_2 \cong 0.8$ with $l_2/B \cong 1$. These are not severe conditions to impose in most applications. Then

$$\frac{Q^2}{2g}\left[\frac{1}{A_b^{\,2}} - \frac{1}{A_a^{\,2}}\right] = y_a - y_b + L \operatorname{Sin} \zeta = \delta y \quad , \tag{12}$$

where

$$A_a = y_a\,(B + y_a \operatorname{ctn} \alpha) \quad ,$$

$$A_b = y_b\,(b + y_b \operatorname{ctn} \alpha) \quad . \tag{13}$$

Then, substituting Eqs 13 in Eq 12,

$$Q = \frac{1}{C}\sqrt{2g\,\delta y} \quad , \tag{14}$$

where

$$C^2 = \frac{1}{y_b^{\,2}(b + y_b \operatorname{ctn}\alpha)^2} - \frac{1}{(\delta y - L \operatorname{Sin}\zeta + y_b)^2\left[B + (\delta y - L \operatorname{Sin}\zeta + y_b)\operatorname{ctn}\alpha\right]^2} \tag{15}$$

For a given site both y_b and δy are usually necessary. But, when the flume operates as a critical depth meter, experiments will make it possible to drop one of the above measurements. Eq 14 is comparable to Eq 10.

IV. THE PRELIMINARY MODEL TESTS

The flumes tested are designated as: (1) modified WSC flume and (2) second modified WSC flume (see Fig. 1). Calibration data were obtained for three roughness conditions for each of the above flumes, i.e., (1) no roughness (an unpainted plywood approach channel twelve feet long), (2) type I roughness and (3) type II roughness.

The model flumes were installed in a channel of trapezoidal cross-section with a 5 per cent slope. The sides of the channel had a slope of 15 degrees from the horizontal. The flume sidewalls had a 30 degree slope with respect to the horizontal. There was an abrupt transition consisting of a vertical wall between the channel and the upstream end of the flume for the tests on the modified WSC flume. The second modified WSC flume had the upstream section of the flume replaced by a smooth transition from the channel to the flume made up from two plane 45 degree isosceles triangles, one on each side of the stream bed.

The roughness may be described as follows. Type I roughness consisted of 1-in. square pieces of 0.5-in. thick plywood nailed to the floor of the channel (not in the flume) on 4-in. centers. They covered the bed and sideslopes for a distance of 3 ft upstream of the flume. Type II roughness was identical in every respect except that the pieces were 0.75 in. thick. These roughnesses were installed in order to determine the effect of roughness variations under field conditions and also to change the Froude number in the approach channel. Minor variations of slope in the field would cause no more variation in Fr than the roughnesses utilized.

Subscript a in the data refers to the upstream measuring station (see Fig. 1). The upstream a corresponds to the modified WSC flume and the downstream a to the second modified WSC flume. The subscript b denotes measurements made midway of the throat.

Model discharges under 0.5 cfs were determined by catching the discharge for a given length of time, weighing it and converting the data to cfs. Rates of flow greater than 0.5 cfs were measured by means of a calibrated 5-in. diameter orifice in a 14-in. pipeline serving the channel in which the flume was located.

Piezometric head measurements were recorded for each discharge in terms of feet of clear water. The head was measured with the floor of the flume as a reference. Data were recorded for both the a and b cross-sections.

V. RESULTS OF PRELIMINARY MODEL TESTS

The preliminary model tests demonstrated that the modified WSC flume (or Venturi flume) holds considerable promise of being a practical device for measuring the flow of steep ephermal streams over a wide range of discharges. However, several precautions must be observed, and additional tests are needed.

While several attempts were made to correlate all the data, regardless of roughness, insufficient data were available to properly compute the Froude number in the approach section. Therefore, the best presentation of the data seems to be a simple plot of ${}_m y_b$ versus Q_m. Fig. 2 is a summary plot of all the data obtained.

Fig. 3 is a plot of ${}_m y_b$ versus Q_m for the modified WSC flume. One sees that for $Q_m < 0.1$ cfs (approaching flow is subcritical) the effect of channel roughness disappears. This corresponds to the results found by such researchers as Parshall. Then, for $Q_m > 3.0$ cfs, the effect of roughness becomes negligible, again because the relative roughness is approaching zero even though the approach velocities are supercritical. In between, which is a very important range of flows for the anticipated application of these data, roughness definitely has an important effect. A couple of points from field current meter ratings during a sustained flow will, however, enable one to get around the roughness problem (also see section VI Recommendations).

Tests were made on the second modified WSC flume because such a design would save nearly 40 per cent on the cost of concrete necessary to build the prototype structure. The initial results (Fig. 4) were, consequently, somewhat disappointing. The calibration curve is too flat (small depth change corresponds to a large change in discharge) to be very usable over an important

range of discharge. Furthermore, the waves that form in this structure have a much greater amplitude than the waves in the first design, particularly within the flume itself.

It is felt that with further study it will be possible to utilize the second modified WSC flume. See section VI Recommendations.

The data reported herein are largely in the supercritical velocity range, the most dangerous from the standpoint of field rating, scour and uplift on the structure. The models were too small to adequately test the lower range of subcritical flows where the flume acts like the conventional critical flow meter. This range is relatively easy to rate either in the field, laboratory or theoretically -- the difficult problem is to find a device that operates well in the supercritical range.

Waves are large and velocities are high in both structures tested. Therefore, in the field, these flumes must be placed on sound rock or the structure will be lost due to scour. The flume must be adequately tied into the rock. Stagnation pressures will be large and uplift will be dangerous.

The problem of instrumentation, recording of the transition from supercritical to subcritical approach velocities, and scour have been considered but are outside the scope of this report.

The available data on the modified WSC flume (Fig. 3) are adequate for preliminary determinations of discharge of prototype designs but more work needs to be done before discharge records obtained by such structures can be classified as "excellent". Reference should be made to section III for equations enabling one to compute a calibration curve for low discharges. Time did not permit carrying out the calculations as a part of this study.

VI. RECOMMENDATIONS

These recommendations are divided into two groups: (A) Modified WSC flume, (B) Future ideas to be tested.

A. Modified WSC flume:

1. Observe the behavior, if possible, of several flumes installed in the field before very much more laboratory data is sought. Pictures, notes, stage data, etc. will be helpful in directing further laboratory studies.

2. Test three hand picked field installations in the laboratory at a scale of 1:2.5 ($\lambda = 2.5$). Topography at each site would be included. The complete range of prototype discharge could be modeled. This would yield information on the affect of roughness, plus give a complete calibration curve for three field sites. These data could be extrapolated to sites of similar topography.

3. Study better instrumentation. Much is needed in the way of means to detect the transition from sub- to supercritical flow.

4. The structure should be installed only in places where sound rock is available. Wave action, scour and uplift pressures need to be considered further.

B. Future ideas to be tested:

1. On the basis of work by Ippen, Knapp, et al, in rectangular flumes, it seems that the second modified WSC flume could be employed if the position of formation of the oblique standing waves could be stabilized by means of slats, etc. placed on

the side slopes of the entrance transition of the flume. This would save several yards of concrete in each structure built.

2. Test a device of the same shape as the second modified design except that at the downstream end of the throat a hinged flip bucket would be built. This flip bucket would deflect the water jet upward so that any scour occurring would be far downstream of the structure. Also, a pressure transducer could be connected to the bucket in such a way that the discharge could be plotted against the transducer output -- thus eliminating stilling wells and water stage recorders.

3. Incorporate sediment discharge equipment with the flume design.

4. Give further consideration to the salt dilution technique. There seems to be several possible ways in which this technique could be applied to the problem under consideration.

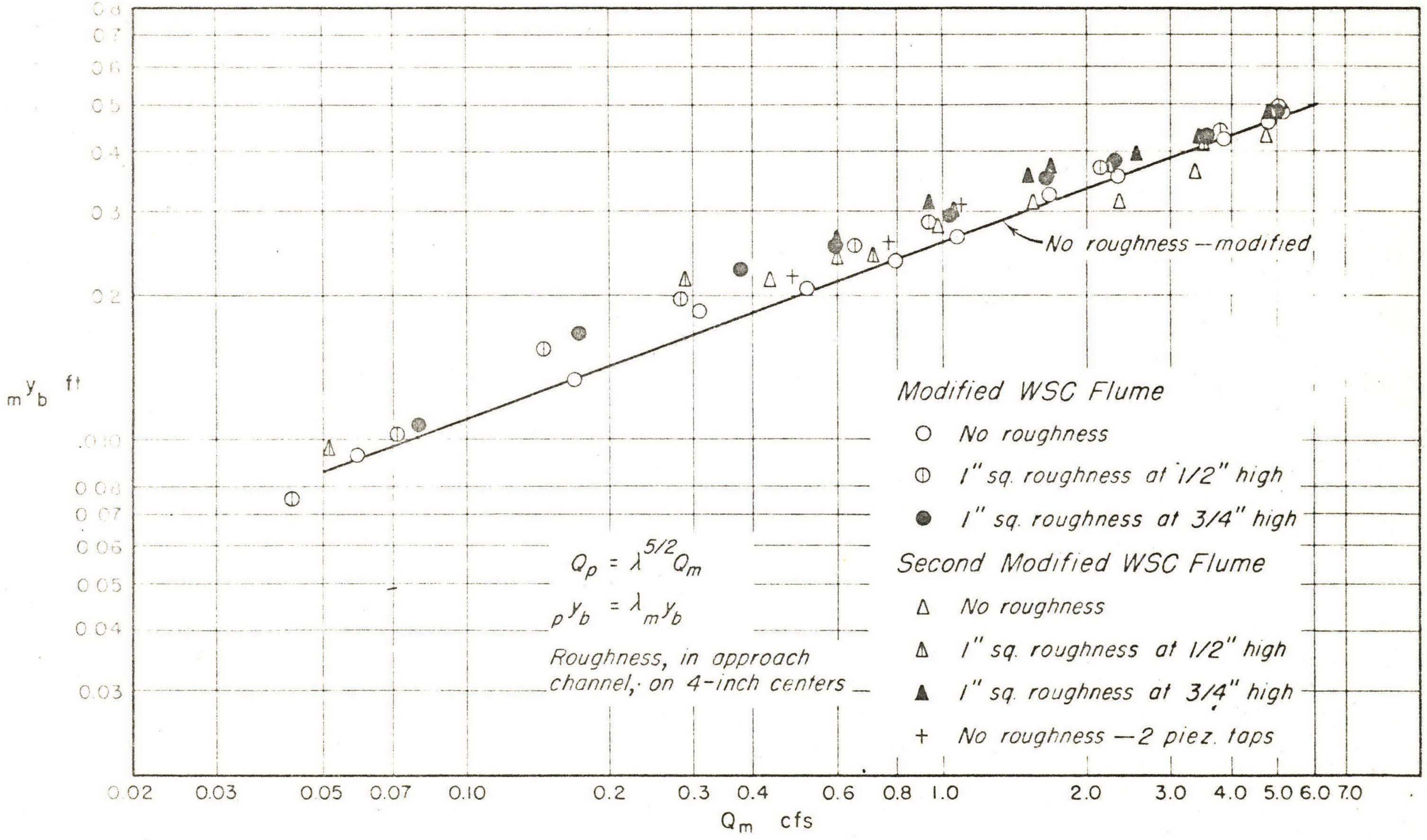


Fig. 2 Summary of all model calibration data

ARC 12/11/56
Colorado A & M College
Civil Engineering Departmen

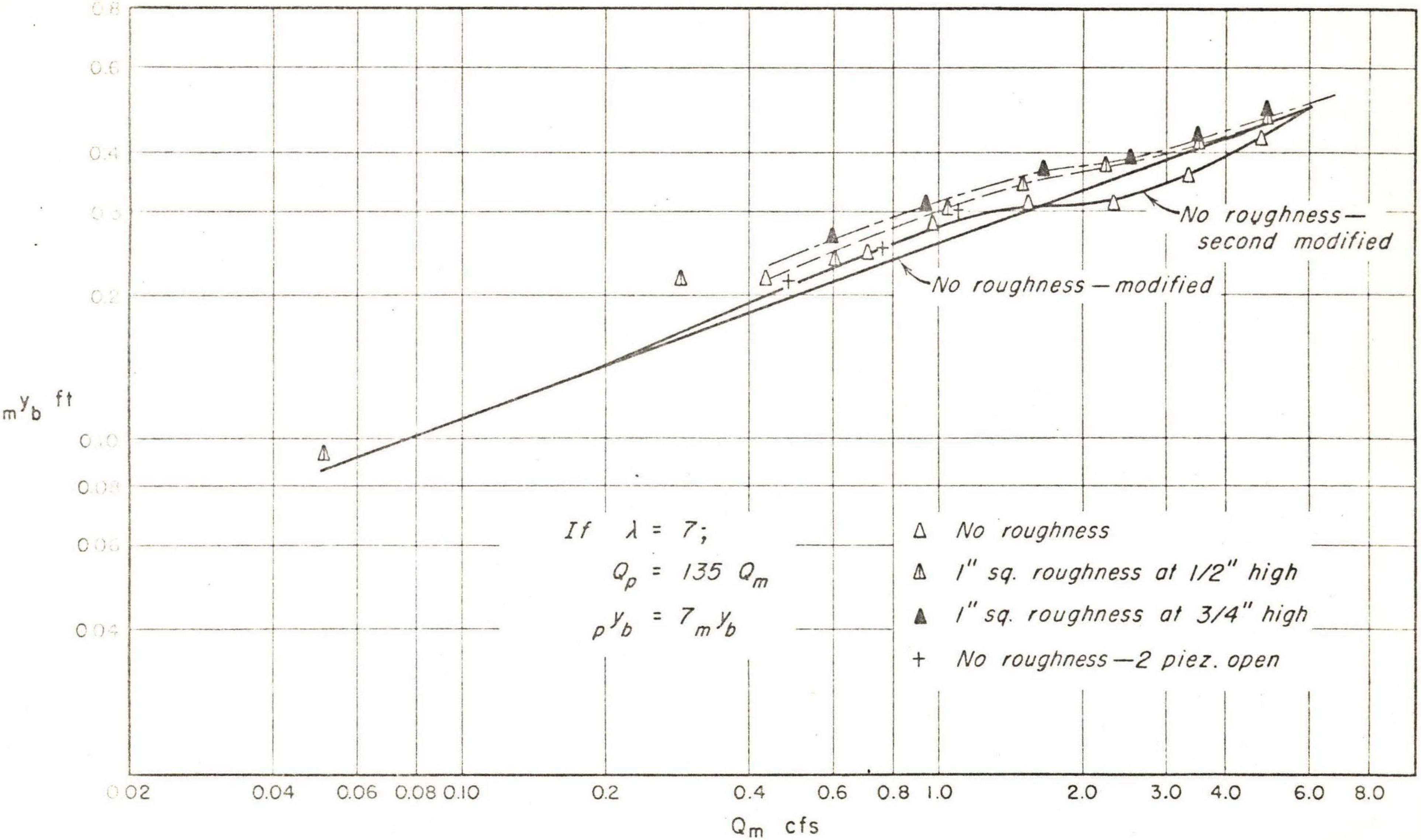


Fig. 4 Plot of $_m y_b$ versus Q_m; second modified WSC flume

ARC 12/11/56
Colorado A & M College
Civil Engineering Department

VII. SUMMARY OF LABORATORY DATA

The data tabulated below are in every case the mean of at least four readings. The piezometric head readings were taken at positions corresponding to the set of taps nearest the bed, shown in Fig. 1. To convert these model data to prototype for a 1/7 scale factor,

$$_p y_a = 7 _m y_a \quad ,$$

$$_p y_b = 7 _m y_b \quad ,$$

$$Q_p = 135 \, Q_m \quad .$$

<u>Modified WSC Flume - No Upstream Roughness</u>

Run No.	$_m y_a$ (ft)	$_m y_b$ (ft)	Q_m (cfs)
1	-	0.048	0.0634
2	0.050	0.132	0.169
3	-	0.093	0.059
4	0.078	0.184	0.306
5	0.106	0.208	0.519
6	0.150	0.236	0.790
7	0.204	0.266	1.060
8	0.287	0.325	1.66
9	0.352	0.354	2.30
10	0.977	0.425	3.85
11	0.544	0.465	4.80
12	0.561	0.482	5.08

Modified WSC Flume - Type I Roughness

Run No.	$_mY_a$ (ft)	$_mY_b$ (ft)	Q_m (cfs)
21	-	0.075	0.0425
19	-	0.103	0.0704
18	0.057	0.156	0.144
20	0.080	0.198	0.280
12	0.149	0.237	0.650
16	0.194	0.285	0.925
15	0.357	0.374	2.15
14	0.496	0.447	3.78
13	0.573	0.498	5.00

Modified WSC Flume - Type II Roughness

Run No.	$_mY_a$ (ft)	$_mY_b$ (ft)	Q_m (cfs)
22	-	0.107	0.0789
23	0.067	0.168	0.171
24	0.099	0.227	0.376
25	0.152	0.256	0.590
26	0.226	0.296	1.025
27	0.310	0.351	1.645
28	0.374	0.384	2.27
29	0.468	0.436	3.49
30	0.566	0.498	4.95

Second Modified WSC Flume - No Upstream Roughness

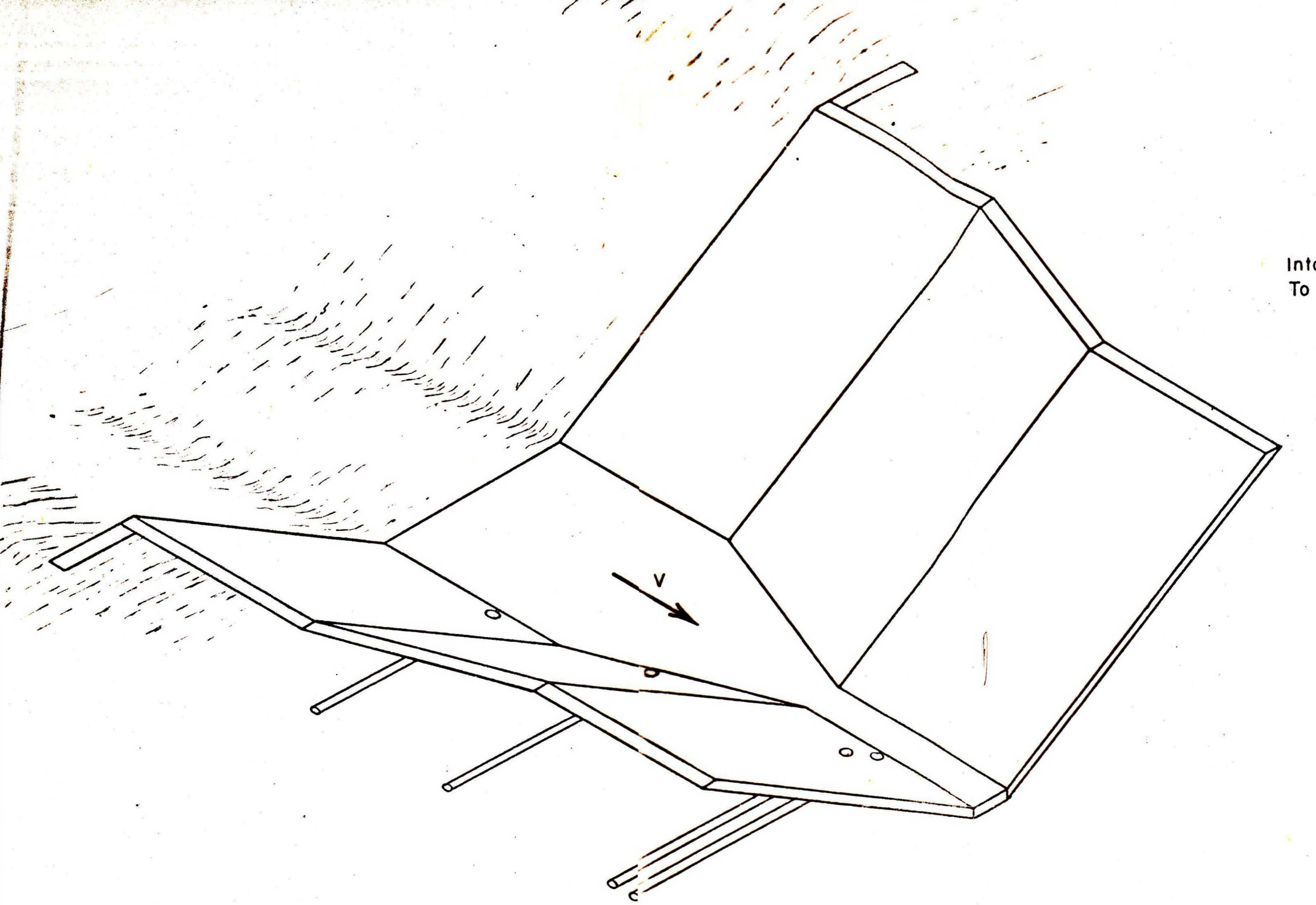
Run No.	$_mY_a$ (ft)	$_mY_b$ (ft)	Q_m (cfs)
35	0.157	0.217	0.429
36	0.185	0.244	0.700
37	0.212	0.282	0.960
33	0.246	0.313	1.51
34	0.319	0.343	2.30
32	0.380	0.361	3.31
31	0.453	0.433	4.75

Second Modified WSC Flume - Type I Roughness

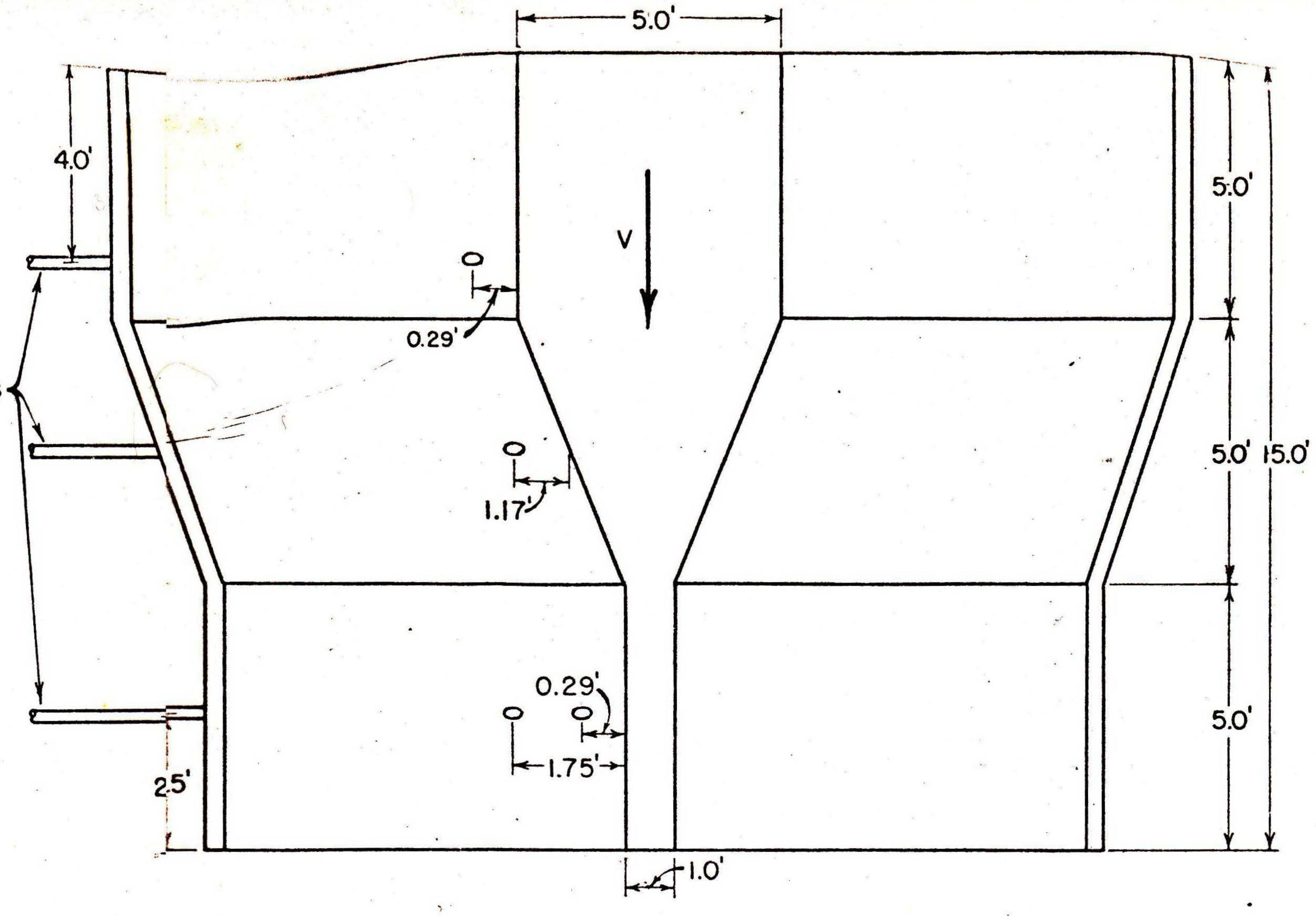
Run No.	${}_mY_a$	${}_mY_b$	Q_m
	(ft)	(ft)	(cfs)
38	0.098	0.094	0.0505
39	0.228	0.217	0.283
40	0.216	0.240	0.600
41	0.272	0.305	1.04
42	0.304	0.350	1.49
43	0.362	0.374	2.20
44	0.396	0.415	3.47
45	0.675	0.471	4.92

Second Modified WSC Flume - Type II Roughness

Run No.	${}_mY_a$	${}_mY_b$	Q_m
	(ft)	(ft)	(cfs)
50	0.227	0.266	0.590
51	0.275	0.311	0.920
49	0.334	0.371	1.640
48	0.382	0.390	2.500
47	0.445	0.426	3.450
46	0.511	0.485	4.920



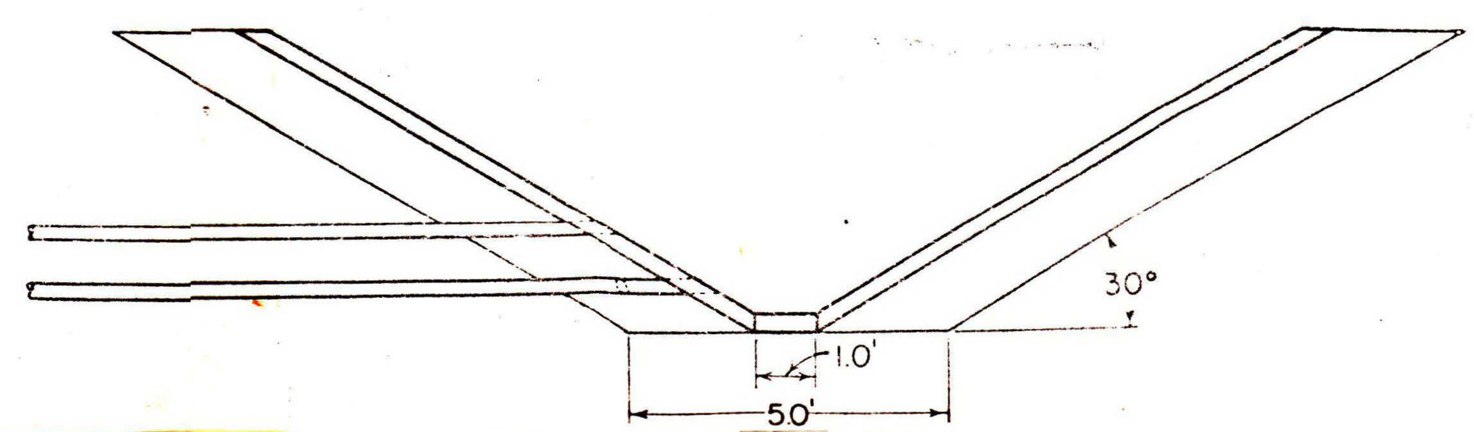
ISOMETRIC VIEW



PLAN

Note: •Bottom of the flume has a slope of 5 percent.

•First modified WSC flume shown above. Second modified WSC flume has upstream 5 feet removed as explained in text of report.



INCLINED ENDVIEW

COLORADO A AND M COLLEGE
FORT COLLINS, COLORADO

MODIFIED WSC FLUME

Scale 1" = 3'

November, 1956

Fig. 1 Flume for flow measurement on steep slopes

BIBLIOGRAPHY

1. Bakhmeteff, B. A. and Matzke, A. B. The hydraulic jump in terms of dynamic similarity. Trans. ASCE, Vol. 101, 1936, p.630.

2. Balloffet, A. Un aforador de resalto, Revista ANDA, No. 108, Buenos Aires, June 1946.

3. Balloffet, A. Aforadores de resalto. Ciencia y Tecnica, Buenos Aires, Vol. 112, No. 559, Jan. 1949.

4. Balloffet, A. Critical flow meters. ASCE Proc., Separate No. 743, Vol. 81, July 1955.

5. Bermel, K. S. Hydraulic influence of modifications to the San Dimas critical-depth measuring flume. Trans., AGU, Vol. 31, Oct. 1950, p763

6. Bhoota, B. V. Characteristics of supercritical flow at an abrupt open-channel enlargement. Ph.D. dissertation, State Univ. of Iowa, Iowa City, Iowa, Dec. 1942.

7. Blaisdell, F. W. Graphical construction of the flow in transitions by the method of characteristics. USDA, Manuscript Report, MN-R-3-24, SCS, St. Anthony Falls Hydraulics Laboratory, Revised Feb. 1946.

8. Blaisdell, F. W. Flow through diverging open channel transitions at supercritical velocities. Technical publication No. 76, SCS, USDA, Washington, D. C., April 1949.

9. Chamberlain, A. R. Application of pressure momentum theory to fluid flow through trapezoidal sections. M.S. thesis, Washington State College, Pullman, Wash., 1952.

10. Citrini. Misuratori a risalto. Politecnico di Milano, 1939.

11. Code, W. B. Farm irrigation structures. Colo. Agric. Exp. Sta., Bul. 496-S, Feb. 1957.

12. Cone, V. M. Flow through weir notches with thin edges and full contractions. Reprint from Journal of Agric. Research, USDA, Vol. V, No. 23, March 6, 1916.

13. Cone, V. M. The Venturi flume. Journal of Agric. Research, Vol. IX, No. 4, Washington; D. C., April 23, 1917.

14. De Marchi and Contessini. Dispositivi per la misura della portata dei canali con minima perdita di quota. L'Energia Elettrica, Jan. 1936, March 1937.

15. Escande. Etude de quelques ecoulements comportants la formation d'une veine coutant, Pub. Scient. et Techniques du Ministere de l'Air, Paris, 1946.

16. Engineering Hydraulics, edited by Hunter Rouse, John Wiley and Sons, Inc. 1950 (proceedings of 4th Hydraulics Conference at State University of Iowa, June 12-15, 1949) Chapter III. Bibliography of 44 references on pp.226-228.

17. Goodell, B. C. A trapezoidal flume for gaging mountain streams. Rocky Mountain Forest and Range Exp. Sta., Fort Collins, Colo., Station Paper No. 2, June 1950.

18. Greve, F. W. Parabolic weirs. Trans. ASCE, Jan. 1921.

19. Harrold, L. L. and Kringold, D. B. Devices for measuring rates and amounts of run-off. USDA, SCS-TP-51, July 1943.

20. Hinds, J. H. The hydraulic jump and critical depth in the design of hydraulic structures. Engr. News Record, VLXXXV, July-Dec. 1920, p.1034.

21. Hinds, J. H. The hydraulic design of flume and siphon transitions. Trans., ASCE, Vol. 92, 1928, p.1435.

22. Hsu, En-Yun. Characteristics of supercritical flow at a gradual open-channel enlargement. M.S. thesis, State Univ. of Iowa, Iowa City, Iowa, Feb. 1946.

23. Ippen, A. T. Gas-wave analogies in open channel flow. Proc., 2nd Hydraulics Conference, Bul. No. 27, Univ. of Iowa, Studies in Engr., Iowa City, Iowa, 1942.

24. Ippen, A. T., Knapp, R. T., Dawson, J. H., Rouse, H., Bhoota, B. V., and Hsu, En-Yuh. High velocity flow in open channels: A Symposium. Trans., ASCE, Vol. 116, 1951. (extensive bibliography).

25. Ippen, A. T. and Harleman, R. F. Verification of theory for oblique standing waves. Trans., ASCE, Vol. 121, 1956.

26. Jameson, A. H. The Venturi flume and the effect of contraction in open channels. Institution of Water Engineers, Incorporated 1911, published at the offices of the Institution, 5 Victoria St., Westminister, S.W. London.

27. Keulegan, G. H. and Patterson, G. W. Mathematical theory of irrotational translation waves, Journal of Research, RP 1273, N. B.S., U. S. Dept. of Commerce, Washington, D. C., Vol. 24, 1940.

28. Keulegan, G. H. "Wave Motion" in Engineering Hydraulics. John Wiley and Sons, Inc., New York, N. Y., 1950, Chapter XI.

29. Khafagi. Der Venturi Kanal. Technische Hochschule, Zurich, 1942.

30. King, H. W. Handbook of applied hydraulics. Third Edition, 1939, McGraw-Hill, New York, N. Y. See pp. 447-492.

31. Modellatori a risalto, Politecnico di Milano, 1941.

32. Moore, A. M. Measuring stream flow under ice conditions. Paper presented to the ASCE, Aug. 1956, Madison, Wisc.

33. Palmer, H. K. and Bowlus, F. D. Venturi flume. Trans. ASCE, Vol. 101, 1936, p. 1195.

34. Parshall, R. L. and Rowher, Carl. The Venturi flume. Colorado A and M College Agric. Exp. Sta., Bul. 265, Feb. 1921, Fort Collins, Colo.

35. Parshall, R. L. The improved Venturi flume. Trans. ASCE, Vol. 89, 1926.

36. Parshall, R. L. The improved Venturi flume. Bul. 336, Colorado A and M Agric. Exp. Sta., March 1928.

37. Parshall, R. L. The Parshall measuring flume. Colorado A and M College, Agric. Exp. Sta., Fort Collins, Colo., Bul. 423, March 1936.

38. Parshall, R. L. Measuring water in irrigation channels. USDA, Farmers Bul. No. 1683, Revised 1941.

39. Preiswerk, E. Application of the methods of gas dynamics to water flows with free surface. NACA, TN 934 and 935, March 1940.

40. Riabouchinsky, D. Sur l'analogue hydraulique des movements d'un f luids compressible, CRAS, Vol. 195, 1932, pp. 998 and Vol. 199, 1934, pp. 632.

41. Robinson, A. R. Parshall flumes of small sizes. Colorado Agric. Exp. Sta., Tech. Bul. No. 61, Jan. 1957.

42. Proceedings of the Sixth Hydraulics Conference, June 13-15, 1955. Edited by Landweber and Hubbard, Univ. of Iowa, Studies in Engineering, Bul. 36 published by the State Univ. of Iowa. (Flow measuring and instrumentation).

43. Scobey, F. C. The flow of water in flumes. Tech. Bul. No. 393, USDA, Dec. 1933.

44. Webb, A. R. Supplemental tests -- weirs with aprons inclined upstream and downstream. Trans. ASCE, Vol. 96, 1932, p. 408.

45. Wilm, H. G., Cotton, J. S. and Storey, H. C. Measurement of debris-laden stream flow with critical depth flumes. Trans. ASCE, Vol. 103, 1938, p 137.

46. Wilm, H. G. and Storey, H. C. Velocity head rod calibrated for measuring s stream flow. Civil Engineering, Vol. 14, 1944, pp. 475-476.

47. Woodburn, G. G. Tests of broad-crested weirs. Trans. ASCE, Vol. 96, 1932, p.403.

48. Water losses under natural conditions from wet areas in southern California. California State Bul. No. 44, Division of Water Resources, 1933.

49. Water measurement manual. U. S. Bureau of Reclamation, Denver, Colo., May 1953. (contains a good bibliography on pp.135-137).

Additional References:

1. Addison, Herbert. Hydraulic measurements. John Wiley and Sons, 1946.

2. Lippincott, J. B. Hydraulic measuring stick. Western Construction News, Aug. 25, 1929, p.424.

3. Wilm, H. G. Measuring flow in open channels. Engineering News-Record, Dec. 5, 1940, p.754.

4. Yarnell, D. L. and Nagler, F. A. Effect of turbulence on the registration of current meters. Transactions ASCE, 1931, pp.788-795, 856-860.

5. Lansford, W. M. A magnetic flow meter. Mechanical Engineering, Jan. 1939, p.20.

6. Fluid meters, 4th edition, 1937, and Flow measurement, 1940, ASME.

7. Nagler, F. A. New flow meter uses side contractions only. Engineering News-Record, Vol. 111, Aug. 3, 1933.

8. Allen, C. M. and Taylor, E. A. The salt velocity method of water measurement. Transactions ASME, Vol. 45, 1923, p.285.

9. Barbagelata, A. Chemical-electric measurement of water. Proceedings ASCE, Vol. 54, 1928, p.789.

10. Schoder, E. W. and Turner, K. B. Precise weir measurements. Transactions ASCE, Vol. 54, 1928, p.789.

11. Cline, C. G. Discharge formulas and tables for sharp-crested suppressed weirs. Transactions ASCE, Vol. 100, 1935, p.396.

12. Greve, F. W. Semicircular weirs calibrated at Purdue University. Engineering News-Record, July 31, 1924.

13. Mavis, F. T., Soucek, Edward, and Howe, H. E. Sutro weir investigations furnish discharge coefficients. Engineering News-Record, Nov. 12, 1936.

14. Villemonte, J. R. Submerged weir discharge studies. Engineering News-Record, Dec. 25, 1947, p.866.